Diagnostic Performance of Ultrafast Brain MRI for Evaluation of Abusive Head Trauma

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ABSTRACT

BACKGROUND AND PURPOSE: MRI with sedation is commonly used to detect intracranial traumatic pathology in the pediatric population. Our purpose is to compare non-sedated ultrafast MRI (ufMRI), non-contrast head CT (nHCT), and standard MRI (stMRI) for detection of intracranial trauma in patients with potential abusive head trauma (AHT).

MATERIALS AND METHODS: A prospective study was performed in 24 pediatric patients who were evaluated for potential AHT. All patients received nHCT, ufMRI brain without sedation, and stMRI with general anesthesia or papoose, sequentially. Two pediatric neuroradiologists independently reviewed each modality blinded to other modalities for intracranial trauma. Inter-reader agreement was performed, and consensus interpretation for stMRI as the gold standard. Diagnostic accuracy was calculated for ufMRI, nHCT, and combined ufMRI with nHCT.

RESULTS: Inter-reader agreement was moderate for ufMRI (k=0.42), substantial for nHCT (k=0.63), and nearly perfect for stMRI (k=0.86). 42% of patients had discrepancies between ufMRI and stMRI which included detection of subarachnoid hemorrhage, and subdural hemorrhage. Sensitivity, specificity, positive and negative predictive values were obtained for any traumatic pathology for each exam: UfMRI (50%, 100%, 100%, 31%), nHCT (25%, 100%, 100%, 21%) and combination of ufMRI with nHCT (60%, 100%, 100%, 33%). UfMRI was more sensitive than nHCT for detection of intraparenchymal hemorrhage (p=0.03), and the combination of ufMRI with nHCT was more sensitive than nHCT alone for intracranial trauma (p=0.02).

CONCLUSION: In AHT, ufMRI, even combined with nHCT, demonstrated low sensitivity compared to stMRI for intracranial traumatic pathology which may limit its utility in this patient population.

Abbreviations: AHT: abusive head trauma; GRE: gradient recalled echo; nHCT: non contrast head CT

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INTRODUCTION

The incidence of abusive head trauma (AHT) in the United States from 2000-2009 is 39.8 per 100,000 children younger than 1 year of age and 6.8 per 100,000 children 1 year of age.[1] The outcomes of AHT victims are worse than those of children with accidental traumatic brain injury including higher rates of mortality and permanent disability from neurological impairment.[2-5] The diagnosis of AHT is frequently not recognized when affected patients initially present to a physician, and up to 28% of children with missed AHT diagnoses may be reinjured leading to permanent neurological damage or even death.[6] Because neuroimaging plays a central role in AHT, continued improvements in neuroimaging are necessary.

Common neuroimaging findings of AHT include intracranial hemorrhage, ischemia, axonal injury, and skull fracture with advantages and disadvantages for both CT and MRI for detection of AHT.[7] A noncontrast head CT (nHCT) is usually the initial imaging study in suspected AHT due to high sensitivity for detection of acute hemorrhage and fracture, a high level of accessibility from the emergency department, and can be performed quickly and safely without the need for special monitoring equipment.[8,9] CT imaging disadvantages include ionizing radiation, particularly in children, and the reduced sensitivity in detecting microhemorrhages, axonal injury, and acute ischemia compared to MRI.[10]

MRI is frequently performed in AHT and adds additional information in 25% of all children with abnormalities on the initial CT scan.[11] Brain MRI can also be useful for identification of bridging vein thrombosis, differentiating subdural fluid collections from enlarged subarachnoid spaces, characterization of the signal of subdural blood, and

demonstrating membrane formation within subdural collections.[12-16] Brain MRI findings have correlated with poor outcomes associated with findings on diffusion-weighted imaging (DWI) and susceptibility-weighted imaging (SWI) in AHT; however, disadvantages of MRI continue to include the need for sedation in children, and compatible monitoring equipment.[17-22] Although there is greater accessibility of CT compared to MRI, the availability of MRI is relatively high and imaging techniques that allow neuroimaging in potential AHT patients without sedation would be valuable particularly given the potential adverse effects of sedation on the developing brain.[23,24]

A potential solution for diagnostic quality brain MRI without sedation in AHT is the use of ultrafast MRI sequences, also termed fast MRI, quick MRI, or rapid MRI. Ultrafast MRI (ufMRI) utilizes pulse sequences which rapidly acquire images, potentially reducing motion artifact and need for sedation. UfMRI has been most commonly used in pediatric neuroradiology for evaluation of intracranial shunts in children with hydrocephalus and majority of reported ufMRI brain protocols include only multiplanar T2-weighted HASTE sequences.[25-34] Consequently, although an ufMRI has been reported to demonstrate limitations for detection of intracranial hemorrhage, the described ufMRI protocol lacked blood-sensitive sequences.[35]

Recently, an ufMRI protocol incorporating sequences in addition to T2 sequences have been reported in pediatric trauma patients.[36] This study did not compare findings to a standard MRI (stMRI) and included a wider age range of pediatric patients such that the value of ufMRI in pediatric abusive head trauma remain uncertain.[36] Therefore, the purpose of our study was to evaluate an ufMRI brain protocol performed without sedation for feasibility in terms of scanning time and diagnostic value as well as diagnostic accuracy compared to nHCT and stMRI brain for the detection of intracranial traumatic pathology in patients with suspected AHT.

MATERIALS AND METHODS

Following institutional review board approval, a prospective study was performed from March 2014 through March 2015 evaluating the diagnostic performance of an ufMRI of the brain performed at a tertiary children's hospital in 24 infants who underwent MRI for the indication of potential AHT. Infants were eligible for enrollment if they had presented acutely to an emergency department, had undergone a nHCT within the preceding 48 hours either performed at a referring institution or our institution, were not intubated or sedated for clinical reasons, and MRI of the head was requested to further evaluate the patient for potential AHT. The following clinical data was collected for each subject: age, gender, and presentation pediatric Glascow coma scale. For all patients, an ufMRI brain protocol was performed without sedation, and depending on age, with or without using a papoose. At our institution a papoose is routinely used below 3 months of age. The ufMRI was immediately followed by a stMRI of the brain with continued use of a papoose or with general anesthesia with a maximum of time interval between completion of ufMRI to start of stMRI of 25 minutes in patients requiring sedation. Patients were not excluded if ufMRI was non-diagnostic, but were excluded if stMRI sequences were non-diagnostic.

MRI imaging was performed with 1.5T or 3T scanners (Avanto and Verio, Siemens Healthcare, Erlangen, Germany). The ufMRI protocol and stMRI protocol details are shown in Table 1. MRI technologists were instructed to only repeat an ufMRI sequence once if there was too much motion artifact. Technical parameters for nHCT were: kVp 100-120, mA 145-185, and

CT Dose Index 17.1-29.4 mGy.

Two board certified fellowship trained pediatric neuroradiologists (S.K., C.H.) with certificate of added qualification in neuroradiology with 3 years and 8 years of experience respectively independently reviewed the ufMRIs followed by a review of the stMRIs. Reviewing ufMRI first without the results of the stMRI allows for a blinded evaluation of the ufMRI. To avoid memory bias for nHCT, these were reviewed by the same two pediatric neuroradiologists at a separate time following a two month interval from the MRI analysis. Axial soft tissue algorithm nHCT at 5mm slice thickness were included for review. Coronal and sagittal reformats were not available in all cases and were not included in the evaluation. The pediatric neuroradiologists were aware the clinical indication was for evaluation of potential AHT but otherwise blinded to the final clinical interpretation as well as additional clinical and radiological information of the patient including skeletal survey results.

UfMRIs, nHCTs, and stMRIs were reviewed for subjective diagnostic quality (diagnostic versus nondiagnostic), and specific assessment was recorded for: subdural fluid collection (unilateral, bilateral, tentorial, presence of subdural fluid-fluid levels, presence of subdural membrane formation/subdural septation), subarachnoid hemorrhage, epidural hemorrhage, intraventricular hemorrhage, intraparenchymal hemorrhage, cytotoxic edema, nonhemorrhagic vasogenic parenchymal edema, parenchymal lacerations, hydrocephalus, midline shift, herniation (uncal, subfalcine, tonsillar), enlarged subarachnoid spaces, and encephalomalacia. Subdural fluid collections were defined as fluid collections located under the dura along the convexities, falx, or tentorium. Fluid-fluid levels were defined as a difference in signal intensity or density which had a meniscus/layering pattern. Subdural membrane formation was defined as an identifiable line/band which separated a subdural fluid collection into more than one

compartment. Subarachnoid hemorrhage was identified as blood localized within the subarachnoid space including basal cisterns or sulci which was identified as hyperdensity on CT and hyperintense signal on FLAIR imaging or hypointense signal on T2*/SWI imaging. Intraparenchymal hemorrhage was defined as intraparenchymal hyperdensity on CT, and focal intraaxial signal abnormality with either low signal on T2W, T2* or SWI images or high signal intensity on T1W images. Cytotoxic edema was defined as an area demonstrating low density on CT involving gray matter, and high signal intensity on DWI images with low signal intensity on corresponding apparent diffusion coefficient map and included diffuse axonal injury, and vascular infarct. Nonhemorrhagic vasogenic parenchymal edema was defined as low density on CT sparing the gray matter, and abnormal T2 signal hyperintensity without associated intraparenchymal hemorrhage or cytotoxic edema as defined above. Parenchymal lacerations were defined as a parenchymal cleft containing CSF and/or hemorrhage which did not correspond to a normal anatomic structure such as a sulcus. Enlarged subarachnoid spaces were defined as subarachnoid spaces measuring greater than 4 mm in thickness. Encephalomalacia was defined as a focal loss of brain volume involving cortex identified on any sequence.

Upon completion of review of the nHCTs, ufMRIs and stMRIs, discrepancies between neuroradiologists were resolved by discussion to establish a consensus interpretation. For the calculation of concordance, an exam was considered concordant if all findings were in agreement, and discordant if there was any disagreement for any of the pathologic categories. K values < 0 are considered no agreement, 0–0.20 as slight agreement, 0.21–0.40 as fair agreement, 0.41–0.60 as moderate agreement, 0.61–0.80 as substantial agreement, and 0.81–1 as almost perfect agreement.[37] Sensitivity, specificity, positive predictive value, and negative predictive value for consensus interpretation for ufMRI, nHCT, and ufMRI combined with nHCT,

respectively, were calculated compared to consensus stMRI as the gold standard. McNemar's test was used to assess for significance of the discordance rate compared to the gold standard for each pathologic entity, as well as the changes in sensitivity between ufMRI, nHCT, and combined ufMRI with nHCT. Statistics were performed using MedCalc Statistical Software version 14.12.0 (MedCalc Software bvba, Ostend, Belgium; http://www.medcalc.org; 2014) with $p<0.05$ considered statistically significant.

RESULTS

The median age was 4 months (range 9 days – 31 months) and male:female ratio was 2:1. The median presentation pediatric Glascow coma scale was 15 (range 13-15). As per study protocol, no sedation was performed during ufMRIs of the brain for all 24 patients. StMRI was performed with papoose in 15/24 (63%) patients and with general anesthesia for 9/24 (37%) patients. UfMRI was performed without sedation in all 24 patients, required less than 2 minutes to acquire all of the imaging sequences, and was of diagnostic quality in all patients while stMRI required general anesthesia in 9 of 24 patients to achieve diagnostic quality and required approximately 15 minutes to acquire all of the imaging sequences. UfMRI sequences and stMRI sequences were considered diagnostic in all patients by both neuroradiologists. Four individual ultrafast sequences were repeated in 3/24 scans compared to a repeat of 11 stMRI sequences in 6/24 scans. All nHCT CTs were of acceptable diagnostic quality.

Summary of the prevalence of imaging findings identified on stMRI is listed in Table 2. The overall prevalence of patients with an abnormal intracranial trauma finding on stMRI was 83.3%.

Binary inter-reader agreement for complete agreement versus any discrepant finding was moderate for ufMRI (k=0.42, 95%CI 0-0.87), substantial for nHCT (k=0.63, 95%CI 0.30-0.96), and nearly perfect for stMRI (k=0.86, 95%CI 0.60-1). Only one patient had an inter-reader discrepancy on stMRI which involved presence of old blood products along the tentorium.

Discrepancy rates for individual findings on the consensus interpretation for ufMRI and nHCT compared to stMRI are listed in Table 3. The only significant discrepancy rate by pathology was the detection of intraparenchymal hemorrhage on nHCT compared to stMRI (p=0.03). For the total discrepancy rates per exam type, there was significance for consensus ultrafast (p=0.004), nHCT (p=0.0003) and combined ufMRI and nHCT (p=0.01) compared to the gold stMRI.

Discrepancies where consensus ufMRI missed but were detected on consensus stMRI included: four patients with subarachnoid hemorrhage, three patients with bilateral subdural fluid collections in which one collection was not identified, two patients with a fluid-fluid level in a subdural collection, and three patients with tentorial subdural hemorrhage. UfMRI demonstrated complete agreement between both reviewers and the stMRI for presence of at least one subdural collection, intraventricular hemorrhage, parenchymal laceration, presence of enlarged subarachnoid spaces, encephalomalacia, parenchymal hemorrhage, herniation or midline shift, and hydrocephalus. There were no abnormal findings described on ultrafast that were normal on stMRI. Examples of ufMRI findings compared to stMRI findings are seen in Figures 1, 2 and 3.

Diagnostic accuracy of consensus comparisons for each test for detecting any intracranial traumatic pathology to gold standard stMRI are listed in Table 4. The differences in the resulting sensitivity of ufMRI versus nHCT and ufMRI versus combined ufMRI with nHCT were not

statistically significant (p=0.13, p=0.48); however the difference in sensitivity of combined ufMRI with nHCT versus nHCT alone was statistically significant (p=0.02).

DISCUSSION

In this study we demonstrate that an ufMRI can be reproducibly performed in pediatric patients referred for potential AHT with subjective diagnostic quality and without sedation. The lack of need for sedation is considered a primary advantage of ufMRI, and this may allow more institutions to perform brain MRIs on these patients without requirement for anesthesiology. Indeed, at many institutions which contain an MRI scanner and even those with 24/7 MRI technologist availability, anesthesiology can become a limiting factor for MRI in pediatric patients. However, ufMRI may be of little benefit if patients are intubated for clinical reasons as stMRI sequences could be performed without loss of spatial resolution.

Although feasible, ufMRI demonstrates decreased inter-reader concordance between the reviewers compared to stMRI. Several of the discrepancies could be identified in retrospect on the ufMRI, but were likely missed due to differences in slice thickness which allows more opportunities to identify a finding on the stMRI compared to the ufMRI. The most frequent discrepant finding involved detection and localization of subarachnoid hemorrhage which was better appreciated on SWI than ultrafast axial T2* images, likely due to both differences in spatial resolution and signal intensity. Although many missed findings on ufMRI can be retrospectively appreciated, given that both reviewers have experience in pediatric neuroimaging, the decreased inter-reader concordance is a limitation of ufMRI compared to stMRI.

When compared to nHCT, ultrafast demonstrated similar discrepancy rates for detection of subdural and subarachnoid blood, but had significantly improved detection of intraparenchymal hematoma. This is likely due T2* sequences, which not only detects acute blood, which would be bright on nHCT, but also chronic hemosiderin, which would be essentially undetectable on nHCT. Although signal loss on T2* cannot differentiate the chronicity of blood, the detection of blood products not seen on nHCT indicates previous injury, and would be helpful when assessing for AHT. We did not find differences in detection of intraparenchymal hemorrhage between ufMRI and stMRI in these patients, however, previous reports have demonstrated greater sensitivity of SWI compared to GRE for detection of cerebral microhemorrhage, and therefore we suspect similarly that the ultrafast T2* images will be less sensitive to detection of cerebral microhemorrhage compared to SWI in a larger cohort.[38] The lack of significance for the detection of cytotoxic edema and enlarged subarachnoid spaces between ufMRI and nHCT was not expected as DWI is more sensitive to cytotoxic edema than CT and T2 HASTE images show the bridging veins within the subarachnoid space more clearly. This may be due to the lower prevalence of these entities in our patient cohort.

Our rationale for combining nHCT and ufMRI is the theoretical algorithm of using both exams as a potential replacement for stMRI, with nHCT providing greater sensitivity for skull fractures and ufMRI for parenchymal injury. While this combination does improve sensitivity compared to nHCT alone and raises sensitivity slightly for intracranial pathology compared to ultrafast alone, the overall low sensitivity likely reflects the high sensitivity of SWI on the stMRI to small hemorrhages overall, particularly in the subarachnoid space. The decreased sensitivity of ufMRI, nHCT and the combination of the two compared to gold stMRI limits our ability to recommend the use of ufMRI in the setting of potential AHT. Institutions that incorporate ufMRI

for pediatric trauma patients should be aware of this potential limitation, and we suggest that if an alternative ufMRI protocol is utilized that a comparison is made to a stMRI to assess the accuracy of the ufMRI.

Discrepancies with ufMRI findings may be reduced if these studies are performed more frequently allowing for increased familiarity of the radiologist to the subtleties of ufMRI findings or could be avoided by reviewing these studies in consensus. Another possibility would be limiting the use of ufMRI for specific indications such as differentiation of enlarged subarachnoid spaces versus chronic subdural hematomas on nHCT or screening for intracranial trauma in patients with low clinical suspicion for AHT which can be followed by a later conventional MRI if necessary. ufMRI was very accurate for differentiation of enlarged subarachnoid spaces from subdural collections, a common difficulty with nHCT. If ufMRI is incorporated into clinical use, we recommend a period of time in which side by side analysis with stMRIs is performed prior to completely replacing stMRI sequences and a low threshold for recommending stMRI.

We could have chosen a broader population to study, particularly any child who came into the emergency department for head trauma, accidental or abusive. However, the included patients in our study is an ideal patient population because of the younger age range, with a higher likelihood of requiring sedation for MRI. However, the goal of MRI in AHT is not necessarily for acute patient management but for a highly sensitive imaging modality to document intracranial injury in a medicolegal context. One could argue that needing a high level of sensitivity requires neuroimaging with the least amount of error in this patient population, and is an ideal challenge to the concept of a fast MRI not needing sedation. Because of the need for detail with regards to medicolegal issues, we did not theorize whether the misses on ufMRI

without a stMRI would lead to immediate poor patient outcome. Since most of the discrepancies were smaller findings, we would expect a limited effect on immediate patient outcome, not considering the known poor long-term outcomes of a child at risk for abuse. In this regard, ufMRI could play a larger role in screening for intracranial pathology where AHT is unlikely.

LIMITATIONS

One limitation of this study is the relatively small sample size. A larger number of patients or a multicenter study may help further the understanding of findings on ufMRI that are reproducibly identified or missed compared to stMRI. Also, nHCT technique was variable due to inclusion of exams from referring institutions rather than repeating the nHCT and exposing the patient to additional radiation. Decreasing doses on head CT lessens the signal to noise ratio and possibly sensitivity to intracranial pathology. However, our institution is a firm adherent to the Image Gently pledge of the Alliance for Radiation Safety in Pediatric Imaging[39] and has consistently lower dose than our referring institutions. Increasing radiation dose at the cost of potential increased risk in malignancy seems counterproductive in this sensitive patient population. Finally, the study was performed across both 1.5T and 3T scanners, which have signal to noise differences. As the ultrafast examination and stMRI examination was performed on the same magnet, this dichotomy in methodology likely has less effect on our results.

A few of our pathologic categories had zero prevalence in this small patient sample, particularly hydrocephalus, herniation and midline shift, and parenchymal lacerations. This is likely due to the exclusion criterion of intubation, resulting in a neurologically intact patient cohort. Hydrocephalus and significant mass effect causing herniation and midline shift would

not be expected to be missed on ufMRI given the gross morphologic changes to the brain. However, parenchymal lacerations, or subcortical tears are uncommon but specific injuries for AHT in very young infants due to immature myelination of the subcortical white matter. Given the small size of these lesions, the sensitivity of ufMRI for this finding is uncertain.

Finally, T1 weighted and T2-weighted FLAIR sequences are conspicuously absent in our ultrafast protocol. These would likely increase both concordance and sensitivity for intracranial pathology. However, these sequences are also sensitive to patient motion due to the length of acquisition even with decreasing NEX and matrix size. Optimization of time versus image signal and resolution by altering these parameters is a further area of study. Furthermore, motion correction techniques, such as radial k-space acquisition, may also be beneficial despite the longer time for acquisition.

CONCLUSIONS

Diagnostic quality ufMRI of the brain can be reliably performed without sedation in patients with potential AHT and requires a very short amount of time to acquire compared to stMRI. However, ufMRI of the brain, as evaluated in our study, demonstrated greater discrepancy between neuroradiologists and had low sensitivity for intracranial trauma findings, particularly subarachnoid hemorrhage, even when combined with nHCT. This limits the use of ufMRI, or combination of ufMRI and nHCT, as a replacement exam for a stMRI in the imaging workup of AHT.

REFERENCES:

1. Niederkrotenthaler T, Xu L, Parks SE, et al. Descriptive factors of abusive head trauma in young children—United States, 2000–2009. Child Abuse Negl 2013; 37:446–455.
2. Duhaime AC, Christian C, Moss E, et al. Long-term outcome in infants with the shaking-impact syndrome. Pediatr Neurosurg 1996;24(6): 292-298.

3. Chevignard MP, Lind K. Long-term outcome of abusive head trauma. Pediatr Radiol (2014) 44 (Suppl 4):S548–S558.
4. Reece RM, Sege R. Childhood head injuries: accidental or inflicted? Arch Pediatr Adolesc Med 2000; 154:11–15.
5. Sills MR, Libby AM, Orton HD. Prehospital and in-hospital mortality: a comparison of intentional and unintentional traumatic brain injuries in Colorado children. Arch Pediatr Adolesc Med 2005; 159(7):665–670.
6. Jenny C, Hymel KP, Ritzen A et al. Analysis of missed cases of abusive head trauma. JAMA 281:621–626, 1999.
7. Vázquez E, Delgado I, Sánchez-Montañez A, et al. Imaging abusive head trauma: why use both computed tomography and magnetic resonance imaging? Pediatr Radiol (2014) 44 (Suppl 4):S589–S603.
8. Jaspan T, Griffiths PD, McConachie NS, et al. Neuroimaging for non-accidental head injury in childhood: a proposed protocol. Clin Radiol 2003; 58:44–53.
9. Ginde AA, Foianini A, Renner DM, et al. Availability and quality of computed tomography and magnetic resonance imaging equipment in U.S. emergency departments. Acad Emerg Med. August 2008, Vol. 15, No. 8. 780–783.
10. Hedlund GL, Frasier LD. Neuroimaging of abusive head trauma. Forensic Sci Med Pathol 2009; 5:280–290.
11. Kemp AM, Jaspan T, Griffiths J, et al. Neuroimaging: what neuroradiological features distinguish abusive from non-abusive head trauma? A systematic review. Arch Dis Child 2011; 96:1103–1112.
12. Kelly AB, Zimmerman RD, Snow RB, et al. Head trauma: comparison of MR and CT: experience in 100 patients. AJNR Am J Neuroradiol 1988;9:699-708.
13. Zimmerman RA, Bilaniuk LT, Farina L. Non-accidental brain trauma in infants: diffusion imaging, contributions to understanding the injury process. J Neuroradiol 2007; 34:109–114
14. Adamsbaum C, Rambaud C (2012) Abusive head trauma (AHT): don't overlook bridging vein thrombosis. Pediatr Radiol 42:1298–1300
15. Hedlund GL. Subdural hemorrhage in abusive head trauma: imaging challenges and controversies. J Am Osteopath Coll Radiol 2012, 1(1):23–30.
16. Bradford R, Choudhary AK, Dias MS. Serial neuroimaging in infants with abusive head trauma: timing abusive injuries. J Neurosurg Pediatrics 12:110–119, 2013.
17. Tanoue K, Aida N, Matsui K. Apparent diffusion coefficient values predict outcomes of abusive head trauma. Acta Paediatr Oslo Nor 2013; 102:805–808
18. Colbert CA, Holshouser BA, Aaen GS, et al. Value of Cerebral Microhemorrhages Detected with Susceptibility-weighted MR Imaging for Prediction of Long-term Outcome in Children with Nonaccidental Trauma. Radiology: Volume 256:3, September 2010.
19. Sieswerda-Hoogendoorn T, Boos S, Spivack B, et al. Abusive head trauma Part II: radiological aspects. Eur J Pediatr 171:617–623, 2012.
20. Babikian T, Tong KA, Galloway NR, et al. Diffusion-weighted imaging predicts cognition in pediatric brain injury. Pediatr Neurol 41:406–412, 2009.
21. Galloway NR, Tong KA, Ashwal S, et al. Diffusion-weighted imaging improves outcome prediction in pediatric traumatic brain injury. J Neurotrauma 25:1153–1162, 2008.
22. Schaefer PW, Huisman TA, Sorensen AG, et al. Diffusion-weighted MR imaging in

closed head injury: high correlation with initial glasgow coma scale score and score on modified Rankin scale at discharge. Radiology 233(1):58–66, 2004.
23. Rappaport BA, Suresh S, Hertz S, et al. Anesthetic neurotoxicity – Clinical implications of animal models. N Eng J Med 372(9), 796-797, 2015.
24. Yu CK, Yuen VM, Wong GT, et al. The effects of anaesthesia on the developing brain: a summary of the clinical evidence. F1000Res 2:166, 2013.
25. Patel DM, Tubbs RS, Pate G, et al. Fast-sequence MRI studies for surveillance imaging in pediatric hydrocephalus. J Neurosurg Pediatr 13:440–447, 2014.
26. Iskandar BJ, Sansone JM, Medow J, et al. The use of quick brain magnetic resonance imaging in the evaluation of shunt-treated hydrocephalus. J Neurosurg 101:147–151, 2004.
27. Ashley Jr WW, McKinstry RC, Leonard JR, et al. Use of rapid-sequence magnetic resonance imaging for evaluation of hydrocephalus in children. J Neurosurg 2005;103:124–30.
28. Forbes KP, Pipe JG, Karis JP, et al. Brain imaging in the unsedated pediatric patient: comparison of periodically rotated overlapping parallel lines with enhanced reconstruction and single-shot fast spin-echo sequences. AJNR Am J Neuroradiol 2003;24(5):794–8.
29. Miller JH, Walkiewicz T, Towbin RB, et al. Improved delineation of ventricular shunt catheters using fast steady-state gradient recalled-echo sequences in a rapid brain MR imaging protocol in nonsedated pediatric patients. AJNR Am J Neuroradiol 2010;31(3):430–5.
30. Missios S, Quebada PB, Forero JA, et al. Quick-brain magnetic resonance imaging for non hydrocephalus indications. J Neurosurg Pediatr 2008;2:438–44.
31. Penzkofer AK, Pfluger T, Pochmann Y, et al. MR imaging of the brain in pediatric patients: diagnostic value of HASTE sequences. AJR Am J Roentgenol 2002;179(2):509–14.
32. Ba-Ssalamaha A, Schick S, Heimberger K, et al. Ultrafast magnetic resonance imaging of the brain. Magn Reson Imaging 2000;18(3):237–43.
33. Singh RK, Smith JT, Wilkinson ID, et al. Ultrafast MR imaging in pediatric neuroradiology. Acta Radiol 2003;44(5):550–7
34. Griffiths PD, Wilkinson ID, Patel MC, et al. Acute neuromedical and neurosurgical admissions - Standard and ultrafast MR imaging of the brain compared with cranial CT. Acta Radiologica 41 2000; 41(5) 401–409.
35. Rozovsky K, Ventureyra EC, Miller E. Fast-brain MRI in children is quick, without sedation, and radiation-free, but beware of limitations. J Clin Neurosci 20:400–405, 2013.
36. Mehta H, Acharya J, Mohan AL, et al. Minimizing Radiation Exposure in evaluation of Pediatric Head Trauma: Use of Rapid MR Imaging. AJNR Am J Neuroradiol 37:11-18, Jan 2016.
37. Fleiss JL: Measuring nominal scale agreement among many raters. Psychol Bull 1971, 76:378–382.
38. Tong KA, Ashwal S, Holshouser BA, et al. Hemorrhagic shearing lesions in children and adolescents with posttraumatic diffuse axonal injury: improved detection and initial results. Radiology 2003;227:332-339.
39. Goske MJ, Applegate KE, Boylan J, et al. The Image Gently campaign: working together to change practice. AJR Am J Roentgenol. 2008 Feb;190(2):273-4

TABLE 1. Ultrafast and standard MRI brain protocols

Exam	Sequence	Parameters					Time
UfMRI		**Magnet Strength**	**TE (ms)**	**TR (ms)**	**Matrix**	**Slice Thickness (mm)**	**Total time:** 1.5T: 1m43s 3T: 1m54s
	Axial T2 HASTE	1.5T 3T	96 98	550 536	192x154 192x154	4 4	23s 19s
	Coronal T2 HASTE		96 98	550 536	123x192 123x192	4 4	23s 19s
	Axial DWI		77 78	4508 12600	128x128 128x128	4 4	36s 46s
	Axial epi T2*		39 39	4190 3350	192x154 192x154	4 4	21s 30s
StMRI							**Total time:** 1.5T: 17m15s 3T: 14m42s
	Sagittal 3D T1 MPRAGE	1.5T 3T	2.98 2.18	2180 1460	192x256 251x256	1.2 0.9	3m53s 3m16s
	Axial T2 TSE		99 116	3950 3980	320x320 307x384	2 2	1m51s 2m12s
	Coronal T2 TSE		109 116	3870 3520	320x320 320x320	2 2	2m12s 4m6s
	Axial T2 FLAIR		152 107	10000 7000	256x256 180x320	4 4	3m0s 1m24s
	Axial DWI		77 78	4508 12600	128x128 128x128	4 4	36s 46s
	Axial SWI		40 40	49 27	195x320 182x256	1.5 1.5	5m43s 2m58s

TABLE 2. Prevalence of imaging findings per patient on standard MRI.

FINDING	PREVALENCE
SUBDURAL COLLECTION	11/24 (46%)
BILATERAL SUBDURAL	10/11 (44%)
SUBARACHNOID HEMORRHAGE	8/24 (33%)
INTRAPARENCHYMAL HEMORRHAGE	7/24 (29%)
INTRAVENTRICULAR HEMORRHAGE	1/24 (4%)
EPIDURAL HEMORRHAGE	3/24 (13%)
CYTOTOXIC EDEMA	4/24 (17%)
PARENCHYMAL LACERATION	0/24 (0%)
VASOGENIC EDEMA	2/24 (8%)
HERNIATION OR MIDLINE SHIFT	0/24 (0%)
HYDROCEPHALUS	0/24 (0%)
ENCEPHALOMALACIA	2/24 (8%)
LARGE SUBARACHNOID SPACES	5/24 (21%)
TOTAL NUMBER OF PATIENTS WITH ANY ABNORMAL FINDING	20/24 (83%)

Table 3. Discrepancy rates for consensus ufMRI, nHCT and combined versus stMRI

	Uf vs stMRI	nHCT vs stMRI	Ultrafast + nHCT vs stMRI
Subdural collection	**0/24 (0%)**	**0/24 (0%)**	**0/24 (0%)**
Bilateral subdural	**3/24 (13%)**	**1/24 (4%)**	**1/24 (4%)**
Tentorial Subdural hemorrhage	**3/24 (13%)**	**3/24 (13%)**	**3/24 (13%)**
Subdural membrane formation	**0/24 (0%)**	**2/24 (8%)**	**0/24 (0%)**
Subdural fluid-fluid level	**2/24 (8%)**	**2/24 (8%)**	**2/24 (8%)**
Subarachnoid hemorrhage	**4/24 (17%)**	**4/24 (17%)**	**4/24 (17%)**
Intraparenchymal hemorrhage	**0/24 (0%)**	**6/24 (25%)***	**0/24 (0%)**
Intraventricular hemorrhage	**0/24 (0%)**	**1/24 (4%)**	**0/24 (0%)**
Epidural hemorrhage	**0/24 (0%)**	**0/24 (0%)**	**0/24 (0%)**
Cytotoxic edema	**0/24 (0%)**	**4/24 (17%)**	**0/24 (0%)**
Parenchymal laceration	**0/24 (0%)**	**0/24 (0%)**	**0/24 (0%)**
Vasogenic edema	**0/24 (0%)**	**1/24 (4%)**	**0/24 (0%)**
Herniation or midline shift	**0/24 (0%)**	**0/24 (0%)**	**0/24 (0%)**
Hydrocephalus	**0/24 (0%)**	**0/24 (0%)**	**0/24 (0%)**
Encephalomalacia	**0/24 (0%)**	**0/24 (0%)**	**0/24 (0%)**
Large subarachnoid spaces	**0/24 (0%)**	**1/24 (4%)**	**0/24 (0%)**
Any discrepancy	**10/24 (42%)***	**15/24 (63%)***	**8/24 (33%)***

Note: * denotes statistically significant McNemar's test ($p<0.05$)

Table 4. Diagnostic performance of consensus ufMRI, nHCT, and combined ufMRI with nHCT compared to StMRI

	Sensitivity	Specificity	PPV	NPV
UfMRI	50% (27%-73%)	100% (40%-100%)	100% (69%-100%)	31% (8%-58%)
nHCT	25% (9%-49%)	100% (40%-100%)	100% (48%-100%)	21% (6%-46%)
Combined Ultrafast with nHCT	60% (36%-81%)	100% (40%-100%)	100% (74%-100%)	33% (10%-65%)

Note: Parentheses denote 95% Confidence Intervals

Figure 1. A 4 month-old with suspected abusive head trauma found to have bilateral subdural collections identified on coronal T2 TSE (A) however the right subdural collection was not prospectively identified on ultrafast coronal T2 HASTE (B).

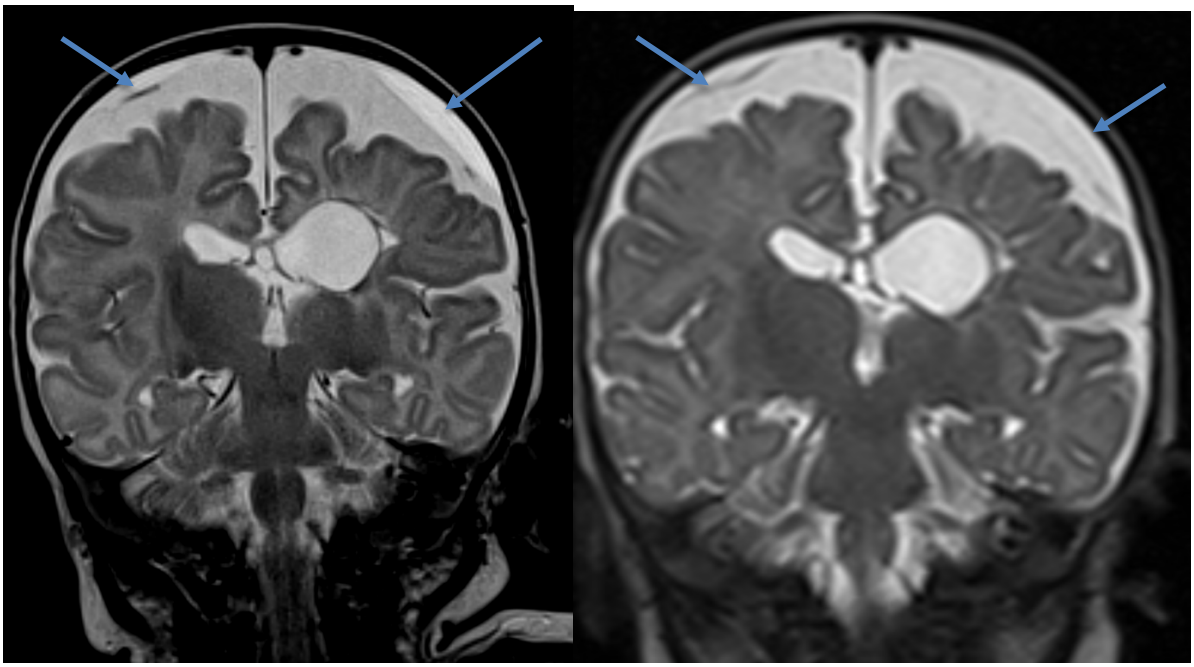

Figure 2. A 31 month old with a suspected abusive head trauma with a subdural hematoma (not shown) found to have subarachnoid hemorrhage in the sulci of the left superior frontal and parietal lobes on axial SWI (A) which was prospectively detected by only one reviewer on ultrafast axial EPI T2* (B).

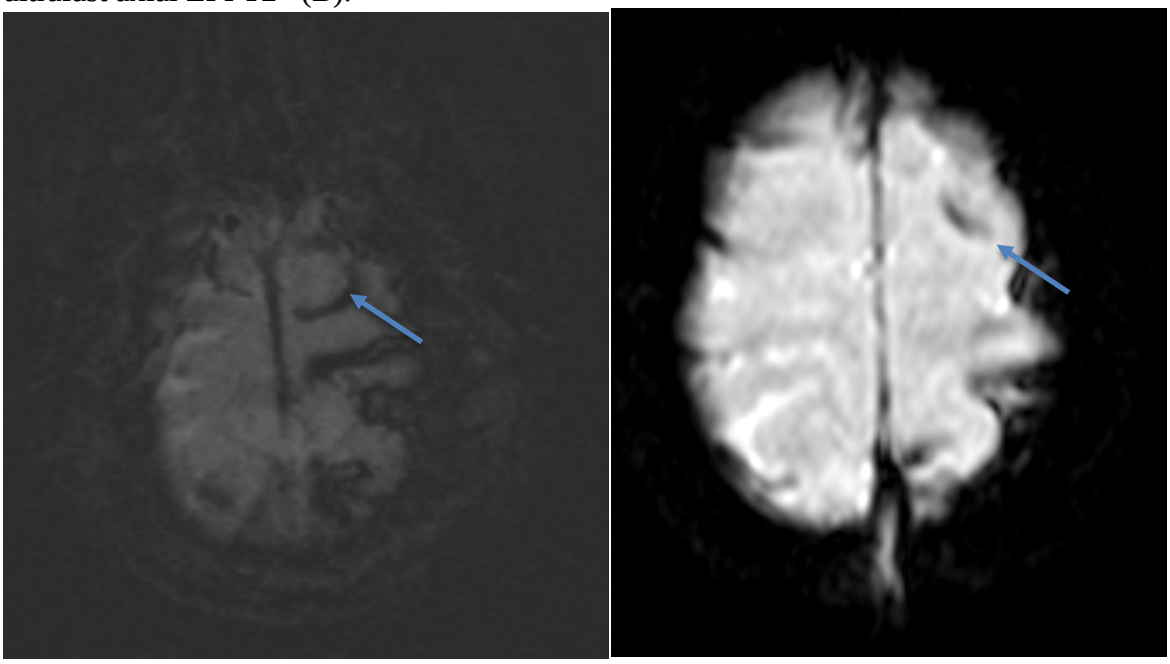

Figure 3. A 10 month-old with suspected abusive head trauma found to have subtle parenchymal edema identified in the left parietal lobe on axial and coronal T2 TSE (A, B) which was not prospectively identified on ultrafast axial or coronal HASTE (C, D).